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RAMIFICATIONS OF EXTENDED STORAGE PERIODS ON WHEELED TACTICAL VEHICLES

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Army Materiel Command

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RAMIFICATIONS OF EXTENDED STORAGE PERIODS ON WHEELED TACTICAL VEHICLES

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FOREWORD

The research discussed in this report was accomplished as part of the Maintainability Engineering Graduate Program conducted jointly by the USAMC Intern Training Center and Texas A&M University. As such, the ideas, concepts, and results herein presented are those of the author and do not necessarily reflect approval or acceptance by the Department of the Army.

This report has been reviewed and is approved for release. For further information on this project contact Mr. R. D. Cook, Intern Training Center, Red River Army Depot, Texarkana, Texas 75501.

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For the Commander

James L. Arnett

James L. Arnett, Director, ITC.

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To determine the effectiveness of current U.S. Army storage and preservation practices, results of extended storage tests are reviewed. Of the four Army preservation environments currently used the standard warehouse was determined

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Reliability and maintainability of stored vehicles was researched with little result regarding reliability, however some trends have been established for availability. A testing procedure for reliability is recommended and outlined.

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CHAPTER I

INTRODUCTION

Importance of Study

Since World War II, the Department of Defense (DOD) has conducted a reserve-readiness program in order to provide material for future military requirements. Due to this program the DOD has set aside massive amounts of equipment to be maintained in storage in a usable condition. The worth of this DOD equipment and material was estimated, by the Prevention and Deterioration Center, Washington, D.C., in 1957 to be 51 bill n dollars. With the introduction of replacement costs and the adjustment of inventories to include new and improved equipment this has undoubtedly escalated to a substantially higher figure. Furthermore the Construction Battallion Center, Port Hueneme, California has estimated that its direct annual storage costs approach 1.5 percent of the acquisition costs of their stores. Applying the 1.5 percent to the 51 billion dollar figure translates to about 760 million dollars the taxpayer pays for the storage of military equipment every year. To ensure that the 760 million dollars is spent effectively, the DOD

recognized that it was of paramount importance that they become experts in storage and preservation techniques. However, even at the highest levels of expertise in the field of preservation, the applied storage techniques will depend on the specified purpose or goal of the storage. To accomplish the goal specified in the reserve-readiness program, the Department of Defense initiated plans to attain maximum stability and reliability from its stored material plus achieve longer shelf lives through better storage practices. As a result they hoped to avoid the costly major overhauls necessary to reverse the extensive degradation that can and will occur during long periods of storage. With these factors in mind it is the objective of this report to determine if current United States Army preservation practices are effective in maintaining a usable condition in its stored equipment.

Area of Study

Few materials withstand the passage of time without some general lowering of quality. Therefore, since some degree of degradation can be anticipated during storage, serviceability limits upon termination cannot coincide with original procurement standards. In this regard, allowances are made when establishing the operational condition to be maintained in stored equipment, with factors affecting serviceability controlled by preservation

methods designed to provide no less than the condition defined. Identification of those factors which exhibit properties promoting deterioration is a key element in storage quality control and the first topic of study in this report. The inspection of factors conducive to deterioration in this report was conducted to establish how they cause destruction to stores and also discover what combinations of factors are most damaging over long periods of time. Once the origin of the degradation is found, the next step is to determine the most effective methods of preservation. In as much as the object of this report is to ascertain if Army storage practices are effective, it compares those methods found to be most effective, through research, to those of the Army.

The most effective methods are, in some cases, not the optimum when cost is considered. The U.S. Army is interested in the maximum protection from degradation for its money, so the analysis of storage costs is seen as an important element in establishing the best techniques for maintaining usable conditions in equipment. This report not only evaluates current storage practices in terms of economic worth, but it extends the train of thought to predict the result of long term storage on the economic life length of Army equipment. It is the considerations surrounding life length that encompass maintainability and

reliability requirements, the two qualities most often specified when setting a usable condition. Storage deterioration causing larger failure rates, thus more down time, necessitating accelerated maintenance schedules and higher costs is the basic premise behind this research on economic life length.

United States Army stores range in nature from simple uniforms to the most complex weaponry. To attempt to establish a routine of storage practices for every type is beyond the limits of this researcher. Therefore a choice was made to confine the study of storage techniques to wheeled tactical vehicles, of which the Army has thousands in storage.

The substantial inventory of vehicles was only the first consideration in deciding upon them as the object of this investigation. Vehicles are complex pieces of equipment with intricate workings made of various metals, plus rubber tires and fabric tarpaulins and tops. Thus wheeled vehicles offer a variety of materials for study contained in one piece of equipment. With this in mind, research was done to determine long term storage effects on wheeled vehicles only. Nevertheless this should not restrict the application of the conclusions drawn herein to vehicles. Using the theory of transferability, equipment with similarities to trucks in structure,

materials, and design may also benefit from them.

Background Information

In a procurement activity, the U.S. Army is particularly interested in determining the Reliability and Maintainability characteristics of a new vehicle. These two qualities are the attributes used to predict the usable condition of a vehicle throughout its life cycle. The failure rate is the one parameter basic, either directly or indirectly, to the calculation of Reliability and Maintainability qualities such as Availability, Mean Time Between Failure (MTBF), Mean Life, Maintenance requirements, and others. Various studies have been conducted by Army agencies to determine a distribution of failures, during operation, from which the failure rate could be obtained directly (8).* Results show that the "bathtub curve" closely approximates the actual failure distribution. The studies resulting in the bathtub curve were based on actual failures observed while the vehicles were in operation. Unfortunately vehicles are not always in operation. It is currently not uncommon for vehicles to experience extended periods of storage. The bathtub curve does not make allowances for degradation resulting from storage, creating discrepancies between its description of the life cycle

*Numbers in parentheses refer to list of references at the end of the paper.

failure rates and the actual failure rates of a vehicle with storage degradation. Therefore this report is an attempt to establish the effects of storage degradation on the operational characteristics of vehicles.

Chapter II is a summary of the literature used to create the foundation on which findings of this report are built. Using this literature, Chapter III presents a general discussion of the physics of degradation in metals and organic materials and Chapter IV outlines the current storage practices used by the Army and their effectiveness in preventing the degradation mentioned in Chapter III. To further discuss the ramifications of storage, Chapter V presents material on the economics of storage while Chapter VI covers Reliability and Maintainability. Finally, Chapter VII summarizes the conclusions drawn throughout the report including some recommendations concerning continued studies into the reliability of stored vehicles.

CHAPTER II

LITERATURE SURVEY

General

The importance of studying long term storage, as stated previously, is unquestionable in the case of the Department of Defense. In contrast, the civilian concern over storage degradation is almost nonexistant as indicated by the lack of literature, found during research, resulting from private industrial studies. An extensive survey of technical literature, including books and journals on the subject of materials handling and degradation of materials in storage, yielded little useful information. It was not until a complete investigation of government studies, cataloged and supplied by the Defense Documentation Center, Alexandria, Va., that most of the knowledge utilized in this report was found.

The severe shortage of information on the long term effects of storage, especially in areas of reliability and maintainability, made it difficult to draw conclusions concerning these factors. However some data was obtainable on reliability and maintainability of aged vehicles in operation. Extending this data to vehicles in storage is

one purpose of this report. All the information found pertained to vehicles and is reviewed here.

Storage Degradation

Knowledge of why material deteriorates while in storage is a necessary background if effective preservation techniques are to be established. To secure such a background, a literature search was conducted to obtain facts on the physics of material degradation. Two reports found were completed by the University of Minnesota while under contract to the U.S. Navy. One report (17) elaborates on the physics of degradation in both metallic and nonmetallic substances. The second University of Minnesota report (18) delves into the intricacies of corrosion as a commonplace element in degenerating the condition of metal parts. Since corrosion is by far the one factor most common to deterioration, additional studies on its long term effect during storage were found. A study performed by the Naval Civil Engineering Laboratory (NCEL) (11) resulted in data concerning rusting of metal components over a five year period. The purpose of the study was to determine the maximum storage period and the best environment and preservation level for long term storage of metals. In addition, two corrosion reports that directly relate to wheeled vehicles were found during the literature survey. The first, accomplished by the U.S. Army Automotive Command

(TACOM) (15) was a test of preservative oils and their effect on the rusting of installed engines of combat vehicles. It provides data on the areas of internal combustion engines which are most susceptible to rusting and the time limits for exposure to corrosive elements. The last report, authored by A.G. Imgram (4), graphically presents the reduction of the burst ratings of hydraulic brake lines due to corrosion.

Concomitant with the researching of the causes of degradation is the establishment of preservation methods in use. A technical report published by NCEL (11) gives a complete summary of the techniques currently in practice, as does the Army Technical Manual on Storage (7). NCEL (10) and the University of Minnesota (17) conducted long term experiments to determine the most effective storage procedures for a group of equipment. The results of those experiments showed controlled humidity warehouses as superior in preservation capabilities, but also found them too expensive as an optimum arrangement for storage practices.

Economics of Storage

Storage cost is obviously an important factor in determining the optimal preservation method. The NCEL study (11) investigated the associated costs and developed an equation describing them. As stated, the total storage

cost is the sum of many individual costs: rehabilitation cost, building cost, maintenance costs, preservative material and application costs, inspection costs, and others. The total cost varies with combinations of storage environments, preservation levels, and time. The NCEL Equation which considers these costs is:

$$W = B_{ij} + N_{ij} + S_{ij}P_{it} + C_jT(D + E_i) + R_{ijt} + L(A_{ij} + H_{ij} + M_{ijt} + K\,F_{ij}U_{ij} + YV_{ij}G_{ij}). \tag{1}$$

An explanation of the terms of the equation and some examples of storage costs are included in Appendix B. Using the above cost equation, curves of total cost vs. storage time, such as the one shown in Figure 1, were drawn and used to compare storage cost to operating cost.

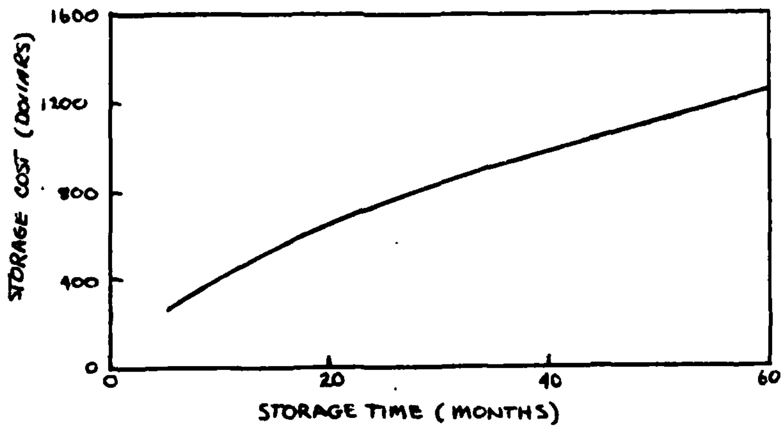

FIGURE 1. STORAGE COSTS VERSUS STORAGE TIME (17)

Data on operating cost was obtained from a Research Analysis Corporation report (13) on the M-151 ¼-ton truck.

Curves of operating cost vs. time were plotted, as indicated in Figure 2, in the report, and used to establish the economic life length of the M-151 at 37,000 miles or, at a use rate of 550 miles per month, approximately 5½ years. With the inclusion of storage in the life cycle this could be either lengthened or shortened depending on factors such as type of storage and when the vehicle is placed in storage. This is discussed in detail in Chapter V.

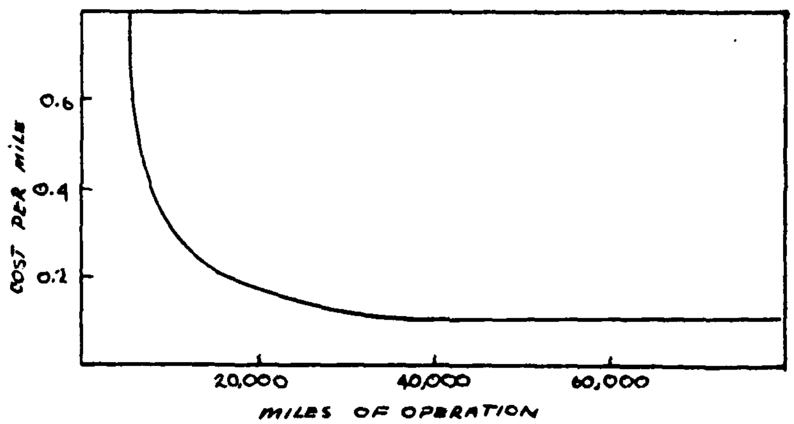

FIGURE 2. OPERATIONAL COST VERSUS TIME (13)

Maintainability and Reliability

Mention has been made that research on the Reliability and Maintainability of vehicles in storage is almost non-existent. The literature search performed was unsuccessful in locating government or civilian documents that dealt directly with Reliability and Maintainability (RAM) characteristics of stored wheeled vehicles. An evaluation of the Army's automotive equipment serviceability criteria

(ESC) performed by the Research Analysis Corp. (14) is the only report found that even vaguely dealt with Reliability. ESC's are color codes assigned to vehicles, based on U.S. Army standards, designed to measure the ability of equipment to perform its primary mission during the 90 days following inspection and rating. The conclusions of the Research Analysis report showed that ESC's are based in many instances on the subjective judgment of an inspector resulting in high rated vehicles performing no better than lower rated ones. To improve upon the ESC method of estimating reliability, the U.S. Army Test and Evaluation Command (TECOM) established a Reliability test procedure (16). The test involves operating a vehicle, recording failures and calculating reliability based on the observed failures. The test assumes random failures and reliability is calculated using the following formula (based on the Chi-Square distribution):

$$R(t) \geq e^{\frac{-t}{M}} \tag{2}$$

where,

R(t) - vehicle reliability
M - one sided lower confidence limit of MTBF
t - mission time.

The possibility of expanding this technique to make it applicable to stored vehicles is considered in this report.

Availability may be defined as the probability that a system will operate satisfactorily under specified condi-

tions at a given point in time. Availability is also a factor that is difficult to define for stored vehicles. Blanchard and Lowery (2) define several types of availability, the most often specified being inherent availability (A_i). This type of availability is calculated as:

$$A_i = \frac{MTBF}{MTBF + MTTR} \, . \tag{3}$$

Here MTBF represents mean time between failures, and MTTR represents mean time to repair. The difficulty in determining MTBF for dormant vehicles is one reason why this equation is not really applicable to those vehicles in storage. However, Tipton conducted a study entitled, "Measuring Dormant Weapon System Availability" (6), that deals with this problem. He used the basic definition of availability to derive an equation for dormant systems. The resulting equation is:

$$A = \frac{1-e^{-\lambda' td}}{td} \tag{4}$$

where,

- A - availability of a vehicle
- λ' - vehicle failure rate in dormant state
- td - time during which the system is dormant.

With this equation and knowledge of the desired availability and expected length of storage the necessary dormant failure rate can be obtained, which is useful in establishing the level of preservation to be applied to a vehicle.

Other sources of general information covering storage, maintainability, reliability, and associated topics were found and listed in the list of references. These sources contributed facts, of lesser significance than those referenced above, to the report which commences in Chapter III with an examination of the physics of storage degradation.

CHAPTER III

PHYSICS OF STORAGE DEGRADATION

Background

In order to establish a firm foundation upon which to build the conclusions of this report, a discussion of the fundamental concepts of corrosion and deterioration of materials is presented in this chapter. In this discussion materials have been grouped into two general classifications; 1) metals, and 2) organic materials. It is not altogether correct to say that these types of materials deteriorate as a result of two distinct causes; however, it can be generally stated that metals deteriorate primarily by an electrochemical process while organic materials undergo chemical reactions. Many of the factors which are influential in the processes of deterioration are everywhere present in the atmosphere and are therefore present with materials in storage. Climatic factors are not always present in the same degree nor do they always act with the same degree of activity. The degree in which these factors are in combination, however, can be responsible for accelerated deterioration or be the cause of some other indirect degradation of material. In order that these

factors be evaluated, they are discussed individually to bring out circumstances under which they must be considered in the preservation of stored materials.

Organic Materials

The basic unit of composition of many organic materials is either cellulose or hydrocarbon derivatives and they can be affected by numerous chemical and physical factors. The chemistry involved in the chemical changes taking place in the deterioration of organic materials is extremely complicated and will not be discussed in this report. It is intended to cover the highlights of the organic materials of primary interest and the factors causing their deterioration. In vehicles, the materials of concern are textiles, plastics, and rubber.

Textiles

Textiles are caused to deteriorate by either biological or chemical-physical agents. According to the University of Minnesota (17) the biological agents are principally microorganisms (fungi and bacteria) and insects; and the chemical-physical agents are sunlight, oxygen, moisture, temperature changes, and other components of the weather. Organic reactions require two reactants. In the case of textiles the fibers themselves are one reactant and any of the deteriorative agents above constitutes the other. The action of biological agents and exposure to chemical-physi-

cal agents constantly causes reactions and it is only the rate of the reaction that can be changed by environment control. By altering the conditions required for a reaction to occur, the rate of the reaction can be reduced or stopped entirely.

Plastics and Rubber

Plastics and rubber are considered in the same light because they have basically the same molecular structure. They are referred to as polymers of high molecular weight. Chemical changes in polymers depend to a large extent upon the basic design of the polymer. Two main classifications of polymers based on the design of their molecular structure are linear or chain polymers and branched network polymers. It is the disruption of the molecular structure, by chemical or physical reactions, that results in degradation. Chemical and physical deterioration of plastics results in cracking, reduced strength, warping, and loss of transparency. The agents conducent to reactions are water vapor, oxygen, and ozone. Of the three, the most important in the process of deterioration is oxygen and the second in importance is ozone. Oxygen and ozone promote reactions which are irreversible and once started little can be done to rectify the condition. In the case of rubber there are opinions (11) that the most severe agents in deterioration are ozone, heat, and oxygen in that order. The degradation

is a result of the same type of chemical reactions that take place in plastics.

Metals

Previously it was mentioned that metals generally deteriorate due to electrochemical reactions. The reactions result in corrosion of metal surfaces which in turn causes decreased performance and increased wear of metal components. To fully understand the process of electrochemical corrosion the University of Minnesota (17) has illustrated the simple case of iron. In general when metals come in contact with water or a solution, there is a tendency for electrically charged ions to go into solution. Since the solution must remain electrically neutral an equivalent number of ions of another element are displaced. In the case of iron and water hydrogen is plated out on the metal surface as a thin invisible film. The plating of hydrogen is illustrated by the chemical equation:

$$\underset{\text{metal}}{Fe} + \underset{\text{ions}}{2H^{+}} \rightleftharpoons \underset{\text{ion}}{Fe^{++}} + \underset{\text{atoms}}{2H} \quad . \tag{5}$$

Further reaction depends on the success in the removal of this hydrogen film. The removal is generally afforded by combining with dissolved oxygen to form water:

$$\underset{\text{atoms}}{2H} + \underset{\text{dissolved}}{\tfrac{1}{2}O_2} \longrightarrow \underset{\text{liquid}}{H_2O} \tag{6}$$

or by escaping as bubbles of hydrogen gas:

$$\underset{\text{atoms}}{2H} \longrightarrow \underset{\text{gas}}{H_2} \quad . \qquad (7)$$

The removal of the hydrogen film permits the reaction to proceed with the accumulation of iron ions which are precipitated out of solution as rust:

$$2Fe^{++} + \tfrac{1}{2}O_2 + H_2O \longrightarrow \underset{\text{insoluble ferric hydroxide (rust)}}{Fe^{+++} + OH} \quad . \qquad (8)$$

There are many factors which determine and control the corrosion reaction. These factors may be classified as being associated with the metal or the environment.

Factors associated with the metal are: 1) electrode potential and 2) hydrogen overvoltage. Electrode potential refers to the electrochemical series of elements and the ability of an element in the series to displace those below it. The farther apart in the series the two elements are, the faster the disposition will take place. A list of the electrochemical series is included in Appendix A. Hydrogen overvoltage is the added resistance on metal surfaces that must be overcome before hydrogen can be liberated as a gas. Low hydrogen overvoltage in the absence of oxygen may lead to an increased corrosion rate. Factors associated with the environment and controlling the corrosion rate are: 1) hydrogen ion activity, 2) oxygen in solution, and 3) temperature.

The importance of hydrogen in the corrosion process is evident from Equation 5, where variations in the hydrogen-ion concentration have an important effect on the corrosion reaction. The general conclusion is that the greater the concentration the greater the corrosion attack. Oxygen in solution is necessary in the removal of hydrogen as water from the metal surface. Because the rate of corrosion is dependant on the removal of hydrogen it is controlled by the amount of dissolved oxygen at the metal surface. Temperature is important in the corrosive process due to its relation to solubility and reaction rates. An increase in temperature generally increases the rate of reactions and reduces the solubility of gases in solution. Therefore an increase in temperature would tend to increase the corrosion rate.

Although vehicles contain textiles, plastics, and rubber in their construction it is the metal of the major components (internal combustion engines, gear boxes, fuel injectors, brake systems, cooling systems, etc.) that is of prime concern in preserving vehicles. Therefore the discussion of corrosion, its prevention, and the Army's methods for storing vehicles will be continued in Chapter IV.

CHAPTER IV

CURRENT STORAGE PRACTICES

General

The intensity of the deteriorative attack by the physical-chemical, and biological agents is, for the most part, dependant upon the prevailing climatic conditions for any given locality. The climatic variables of most concern, from Chapter Three, are moisture, light, atmospheric oxygen and ozone and, in addition, atmospheric contaminants such as dust, dirt, and sand. The degree of deterioration resulting from exposure to these elements can be determined by defining a material in terms of its susceptibility to deterioration by any of the climatic factors. Therefore any steps taken to reduce the severity of exposure will result in less deterioration. For wheeled vehicles the U.S. Army's preservation techniques and storage methods are intended to reduce exposure to the corrosion causing elements of the environment. The Army Technical Manual specifies the four basic types of military storage environments. These are open air, sheds, standard warehouses, and controlled-humidity warehouses. There have been some studies conducted to determine the effectiveness of these four storage envi-

ronments in preventing corrosion.

Effectiveness Of Storage

Two of the studies mentioned above were conducted by the U.S. Naval Civil Engineering Laboratory and a third by the Tank Automotive Command. The NCEL reports deal with a five year test to determine the effectiveness of the four types of storage in preventing overall corrosion while the TACOM report deals strictly with the degradation of internal-combustion engines.

Open-air, sometimes called slab, storage consists of a concrete floor usually bounded by a curb. No protection from the weather is offered and vehicles are stored fully exposed. Shed storage is a three sided metal or wooden structure with a concrete floor and roof offering, though not complete buildings, considerably more protection than open-air storage to the rigors of weather. Widely used commercially are standard warehouses. They are complete buildings and except for infiltration of outside humidity offer complete protection from the weather. Controlled humidity warehouses offer the complete protection of the standard warehouse plus the extra benefit of controlled moisture level in the air. Along with these storage environments two types of preservation levels are used by the Army. The first, denoted as "domestic", is a cursory treatment consisting of a preservative compound,

P-1*, applied to exterior nonmachined ferrous metal surfaces and placing regular in-service oils and greases in transmissions, differentials, and other working parts of the equipment. Domestic processing also includes retouching paint and taping shut openings that might admit moisture. Second is "contact" preservation which is a thorough treatment with a range of p-type preservatives applied to all corrodable exterior and interior surfaces. Exterior surfaces are repainted where necessary and openings are sealed against moisture. Also packaging and packing of components is done when applicable.

In a five year test of the storage environments NCEL (11) placed both a domestic and contact treated vehicle in each of the four, including a 40 percent and 50 percent relative humidity warehouse. Results of the five year storage showed that protection is poor in the open air storage, fair in the shed, good in the standard warehouse, and better in humidity controlled warehouses. Also in comparison to domestic treatment, contact preservation decreased rust incidence by an average of 54 percent. Throughout the range of storage environments, it is of interest to note that the trucks in open air storage were reported by NCEL (11) to have serious rusting conditions

*P-1 preservative is a corrosion preventive compound which dries to a thin hard film after application.

regardless of preservation and had to be removed from the test after 30 months to prevent permanent irreversible damage. Conversely the trucks placed in the controlled humidity warehouses showed no rust at all after five years of storage. Curves of storage time versus rust count and definitions of the rusting conditions found during the test are included in Appendix A. To substantiate these results the TACOM Engine Corrosion study (15) determined that after three years of outdoor storage, seven of eight engines experienced sufficient corrosion to make satisfactory operation questionable without considerable rework.

The three tests discussed above indicate that the most effective storage environment is the controlled humidity warehouse. In the light of the Chapter III discussion on factors promoting corrosion, these results are not surprising. From that discussion, limiting the moisture level at the metal-atmosphere interface, as is accomplished by controlling humidity, would confine ionization thus retarding corrosion. Controlled humidity warehouses, however, are also very expensive in comparison to the other three storage environments and since the usable condition defined by the Army may allow some rusting, controlled humidity is not necessarily the optimum storage environment. To determine an optimum storage method, costs of the four environments will have to be studied. Fortunately such a

study has been performed and is presented in Chapter V along with considerations of economic life of wheeled vehicles.

CHAPTER V

ECONOMICS OF STORAGE

General

In Chapter IV various storage environments and their relative ability to protect vehicles from elements of degradation were described. Although this data is informative, it does not represent the whole picture concerning storage effectiveness. Missing are the important facts of storage economy. Storage economy is the dollars-and-cents talk about the cost of preserving Army equipment, the factors governing the expenses, and the most cost effective method of storage.

To evaluate costs NCEL (17) collected extensive cost data while conducting a five year storage test. Data on the four Army storage environments was gathered and comparisons made concerning the least expensive and the most effective, in preventing rust, per dollar cost. While the costs based on the NCEL test might not necessarily reflect actual conditions, they should be sufficiently illustrative to provide a useful guide for predicting actual field storage costs.*

*The costs presented herein were taken from the NCEL report and represent 1962 dollars.

Cost Factors

As previously mentioned, total storage cost is the sum of many individual costs. Total cost also varies with combinations of storage environments, preservation levels, and time. For example, there is no construction cost if equipment is stored outdoors on the ground, but there is a sizable construction cost if equipment is stored within a controlled humidity warehouse. Yet, equipment stored outdoors must be thoroughly preserved and inspected frequently, whereas equipment stored indoors requires less preservation and in some cases a minimum of inspection. Influencing all of this is time. An item to be stored for a few days may be kept outdoors with little preservation, but a few years of storage might require other storage environments and extensive preservation. To determine which combination of storage environment and preservation level costs least, NCEL has formulated an equation in which the sum of all the individual costs are equated to the total cost. Previously labeled Equation 1, it is repeated here for convenience:

$$W = B_{ij} + N_{ij} + S_{ij}P_{it} + C_jT(D + E_i) + R_{ijt} + L(A_{ij} + H_{ij} + M_{ijt} + K\,F_{ij}\,U_{ij} + YV_{ij}G_{ij}).$$

This assumes that, in all cases, equipment is stored new and has not yet deteriorated. A brief explanation of each factor is given here with a more complete description in

Appendix B.

- A - The labor hours to initially prepare for storage
- B - Material cost to initially prepare for storage
- C - Square footage required for storage
- D - Unit fixed cost of storage per square foot per month
- E - Storage maintenance cost per square foot per month
- F - Labor hours for item inspection
- G - Labor hours for operational testing only
- H - Labor hours for depreservation
- i - Subscript that denotes type of storage environment
- j - Subscript that denotes type of item stored
- K - Ratio of sample size to lot size
- L - Hourly labor charge
- M - Man-hours for rehabilitation
- N - Material cost for crating, dunnage , boxing, etc.
- P - Original cost of item less depreciation
- R - Parts cost for rehabilitation
- S - One (1) if item is found to be unrepairable
  Zero (0) otherwise
- t - Subscript that denotes storage time
- T - Storage time in months
- U - Number of inspections
- V - Number of operational tests
- W - Total storage cost
- Y - Ratio of operationally tested items to lot size

In testing for the most economical environment NCEL placed a 2½-ton 6x6 dump truck and a ¼-ton 4x4 Jeep in each of the four environments with domestic and contact preservation for a period of 5 years, or 60 months. The total storage costs resulting from the application of Equation 1 are tabulated in Table 1. Equipment was inspected every 3 months in open air, 6 months in the shed, and 12 months in the remaining environments. Of course not all factors of Equation 1 were applicable; those that were not were set at zero. It is also assumed that the vehicles tested were representative of wheeled vehicles in general. Results of

five years storage show the standard warehouse with domestic treatment to be the most economical. Since the total

TABLE 1.

60-MONTH STORAGE COST FOR WHEELED VEHICLES

Environment	Treatment	Cost ($)
Standard warehouse	Domestic	1242
Standard warehouse	Contact	1344
Shed	Domestic	1410
50% RH warehouse	Contact	1585
40% RH warehouse	Contact	1619
50% RH warehouse	Domestic	1674
40% RH warehouse	Domestic	1708
Shed	Contact	1732
Open air (30 months)	Domestic	595
Open air (30 months)	Contact	713

cost equation includes rehabilitation costs, or the cost of restoring a vehicle from a degraded state to an operational condition, the total cost comparison is a direct indication of the cost effectiveness of a storage environment. That is, the lowest cost indicates the most cost effective. In this case the standard warehouse with domestic preservation is the most efficient storage environment even though previous test results showed controlled humidity warehouses as the best environment for preventing storage degradation. Mention should be made that the vehicles in open air storage were removed after 30 months to prevent permanent damage due to corrosion.

To determine the possible variation that could be ex-

pected in the cost figures, NCEL conducted sensitivity tests. These tests were intended to discover which costs, of the equation, were most influential in altering the total cost when high and low values were experienced. NCEL found that large fluctuations in both labor and rehabilitation costs caused increases (or decreases) of approximately 8 percent in total cost. Since the change takes place in costs for all environments the relative standing of their effectiveness does not change.

Economic Life Length

An important consideration in the management of a fleet of vehicles is the knowledge of a vehicle's useful life. To determine the most economic time for replacing a vehicle, the Army uses the point in time when it is least expensive to operate with respect to the total accumulated miles, defined as the economic life length of the vehicle. Since storage can interrupt a vehicle's operational life and at the same time contribute some cost to the economic life, it should be of interest to determine how long periods of storage affect the length of the economic life.

Research Analysis Corporation (13) has determined the economic life length of ¼-ton Jeeps to be in the 37,000 to 47,000 mile range, while Bell and Miduski (1) estimate the economic life of 2½-ton trucks at 60,000 miles.* To obtain

*These trucks are assumed representative of wheeled vehicles in general.

these figures the authors gathered data concerning cumulative maintenance costs, initial procurement, and delivery costs, and averaged their total over a period of miles.

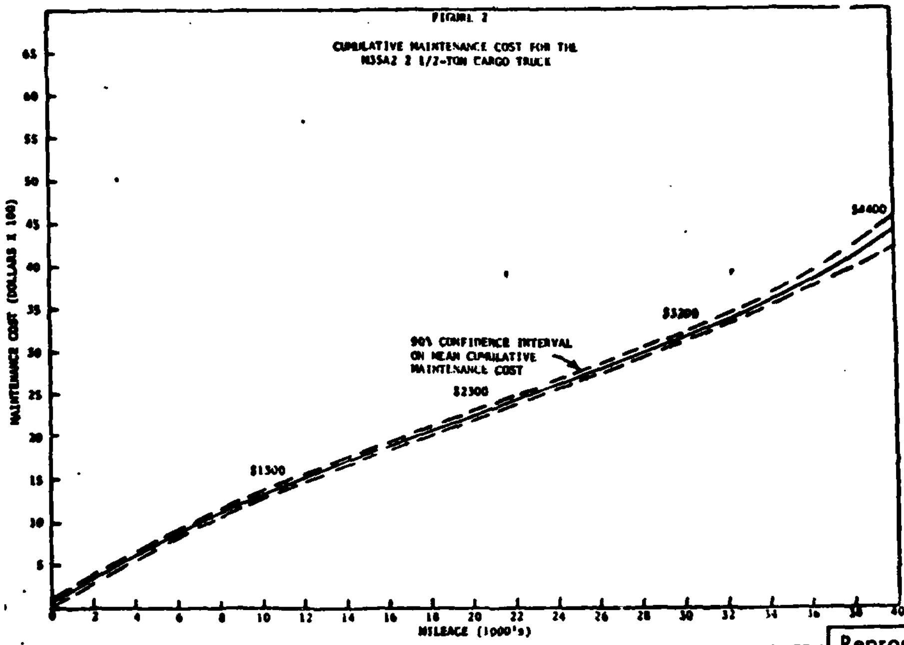

FIGURE 3. CUMULATIVE MAINTENANCE COST (1)

Figure 3 is a curve of cumulative maintenance costs from Bell and Midouski, and Figures 4a and 4b are the average cost curves taken from both studies, respectively. The examination of storage cost effect on the shape of these curves reveals two possibilities: 1) the storage of a new vehicle with no or very little mileage and, 2)a used vehicle with substantial mileage. The first case results in no change in life length. This is due to storage taking place before the vehicle is put into operation, thus the storage

cost can be considered as additional acquisition costs. As a result, only a shift upward takes place in the curve with no change in shape occurring. The minimum is at the same

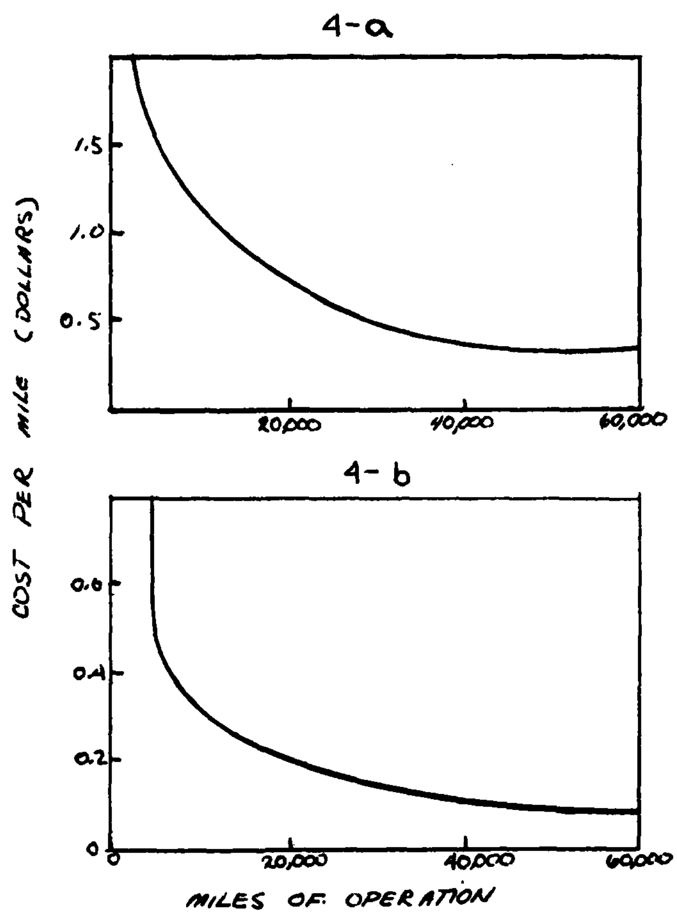

FIGURE 4. AVERAGE OPERATING COSTS (1,13)

place in time, which means no change in life length. In the second case, for a vehicle with substantial mileage, a long term of storage could result in costs that would never be recovered. This situation is illustrated in Figure 5 where a truck with 30,000 miles was stored for five years in the most effective environment (standard warehouse, domestic preservation). The figure shows that, after storage, a level of cost per mile lower than the prestorage level is never reached. This result indicates that for vehicles with high accumulated mileage it is more economical to continue operation than store them for a lengthy period. The relationship just described varies with time in storage and accumulated mileage. For instance, a truck with 30,000 miles stored for one year will eventually recover the storage expenses. This is also shown in Figure 5. It should be noted that in the previous illustration the costs of storage were taken from the results of the NCEL report. The assumption of the NCEL cost equation, new vehicles with no mileage, does not apply in the second case where used vehicles are analyzed. It was assumed that the equation would suffice for illustrative purposes because of the expected increase in storage costs that would accompany a used vehicle. Therefore the NCEL equation would yield a conservative estimate for the demonstration.

The comparisons of economic life length were built on

the assumption that the trucks were restored to their prestorage condition. The validity of this assumption can be questioned especially in the light of some research that has shown that rebuilt vehicles do not perform as well as newly procured ones. To examine the performance of stored vehicles, Chapter VI discusses their reliability and maintainability characteristics.

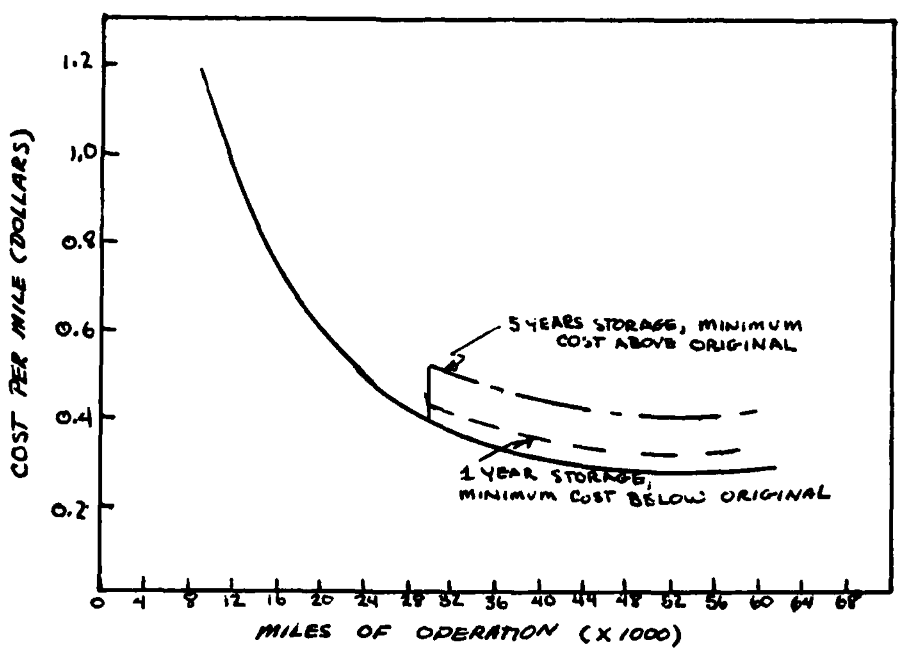

FIGURE 5. EFFECT OF ADDED STORAGE COST ON ECONOMIC LIFE

CHAPTER VI

RELIABILITY AND MAINTAINABILITY

Availability

Availability may be defined as the probability that a system or equipment will perform satisfactorily under stated conditions at any given point in time. This definition excludes ready time, preventative maintenance time, logistics time and administrative downtime. Commonly called inherent availability, this quality is not usually defined for stored equipment. The difficulty in obtaining the mean time between failure (MTBF) necessary for Equation 3 is responsible for the lack of inherent availability specifications for stored vehicles. Tipton has developed a method to help with this problem, in his dormant system availability, that takes into consideration: 1) failure rates of components while in the dormant state, 2) failure rates of the same components while they are being checked out, 3) the time during which the system is in a dormant state, 4) the required time to perform a system. Tipton's general equation is:

$$A = \frac{\dfrac{1 - e^{-\lambda' td}}{\lambda'} + tc}{(td + tc) + m(\lambda' td = \lambda\, tc)} \qquad (9)$$

where,

A - availability of periodically checked components
λ' - failure rate in the dormant state
λ - failure rate in the checkout state
td- time during which equipment is dormant
to- system checkout time
m- average time required to repair a component.

The assumption here is that the component failures occur randomly and therefore a constant failure rate describes the dormant state. A failure in storage is considered to be a component that requires extensive repair or replacement due to corrosion, or some other form of degradation, that has rendered it non-operable. For continuously monitored (continuous checkout or operation) systems, Equation 9 reduces to the standard form on the inherent availability equation (Equation 3):

$$A = \frac{1}{1 + m\lambda} \qquad (10)$$

where,

A - availability
m - average repair time of a failed component
λ - Failure rate in active (checkout) state.

For a system that is not checked at any point of its dormancy, Equation 9 reduces to:

$$A = \frac{1 - e^{-\lambda' td}}{td} \qquad (11)$$

where,

A - availability
λ' - failure rate in dormant state
td- time during which system is dormant.

The equations that Tipton developed will yield the availability of a stored truck if the dormant failure rate is known. However, there is a lack of information on the dormant failure rate of stored vehicles and at best only a guess about the value that should be used in Equation 9 can be made. Even though an exact value for availability cannot be obtained the relationship between the length of storage and availability can be illustrated. Tipton plotted values of the exponent td versus availability for the case of nonchecked components. The negatively sloped curve

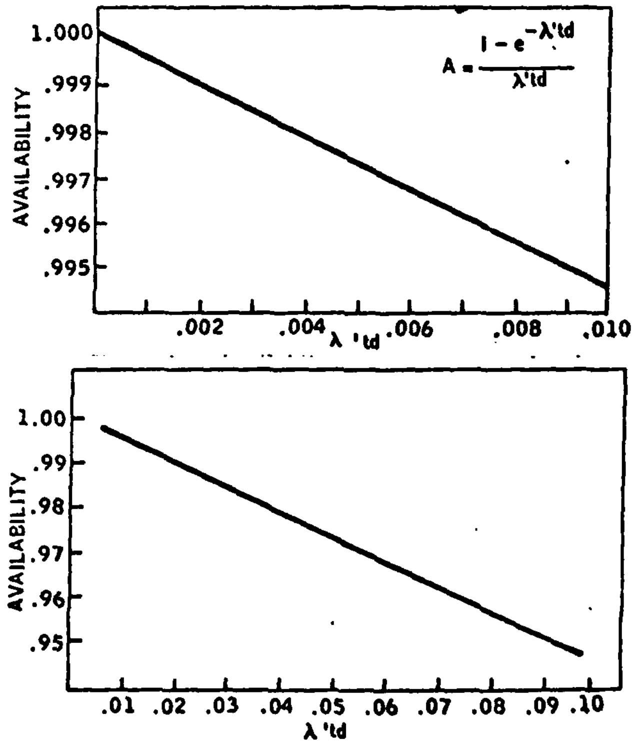

FIGURE 6-A. AVAILABILITY OF NONCHECKED COMPONENTS (6)

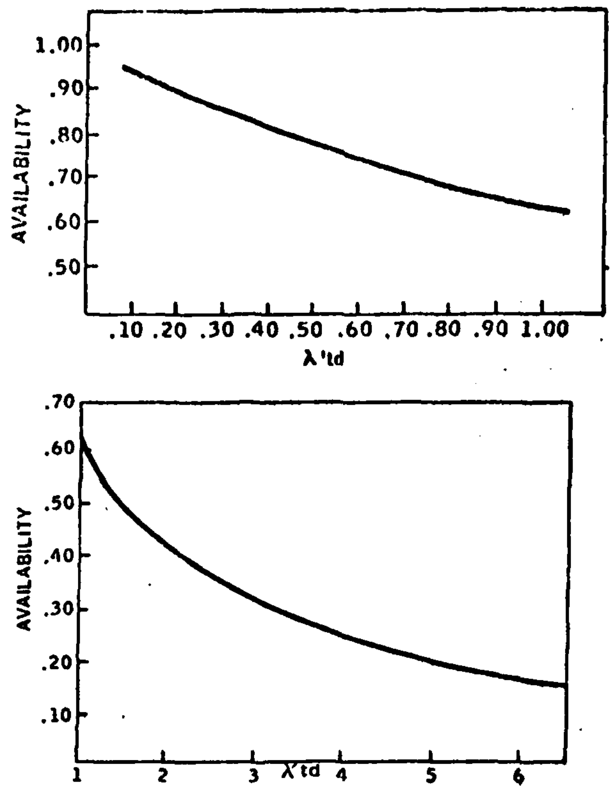

FIGURE 6-B. AVAILABILITY OF NONCHECKED COMPONENTS (6)

of Figure 6 indicates that for some constant failure rate λ', availability decreases with increasing values of td or time in storage. Some simple calculations using the general equation will yield the same inverse relationship, with a lesser negative slope. The graphs of availability versus td also lend some insight into how stringent the preservation levels for different lengths of storage should be.

For instance, to maintain an availability level of 0.99, Figure 6 indicates that the exponent value must be 0.02. For a storage period of 1 year the MTBF should be:

$$\lambda' td = 0.02 \qquad MTBF = \frac{1}{\lambda'} = \frac{td}{0.02} = 50 \text{ years.}$$

Using similar techniques the MTBF for a storage period of 5 years should be 250 years or five times as large as that for one year. Since it takes more extensive preservation to achieve a longer mean time between failures, the above calculations show that more and better care should be taken in longer periods of storage.

Reliability

Earlier in the report, mention was made of the serviceability criteria used by the Army to determine the ability of a vehicle to perform its mission for 90 days following inspection and rating. It was also established that the Research Analysis Corporation report (14) found the equipment serviceability criteria (ESC) to be too subjective in determining ratings for what is essentially the reliability of a vehicle. Although the ESC is not a probability it attempts to accomplish the same task as is defined for reliability; that is, to determine the probability that an item will perform for a specified interval under stated conditions. The ESC ratings are applied to vehicles, rathe

than an actual reliability figure, after storage, because of the ease in which they can be administered.

To determine the reliability of a post-storage vehicle, analytically, requires knowledge of the new failure rate; which is a combination of the dormant failure rate and the active failure rate taken from the bathtub curve. If a constant failure rate is assumed during storage and the vehicle is considered in the infant mortality stage of the bathtub curve, a very complicated convolution to gain the new failure rate will result. If the simplifying assumption is made that the vehicle is restored to its original condition upon removal from storage, the bathtub curve can be used directly to calculate reliability. In an effort to establish the reliability of a vehicle, the Army Test and Evaluation Command (TECOM) (16) developed a service test procedure. Before a vehicle is put into service it is operationally tested according to this procedure and the collected data is applied to the following equation (Equation 2):

$$R = e^{\frac{-t}{M}}$$

where,
R = vehicle reliability
M = MTBF estimate calculated by $\frac{2T}{\chi^2_{\alpha,2r+2}}$
$\chi^2_{\alpha,2r+2}$ = the percentage point of the Chi-Square distribution for 2r+2 degrees of freedom
T = total test time
r = the number of failures observed
α = 1-(confidence level)
t = mission time.

This equation is based on the fact that failures are sampled from a population of failures that are randomly distributed. The TECOM equation could be applied to a vehicle in storage because it estimates the failure rate through sampling failures therefore avoiding the complications of a convolution.

More explicit information of the failure rate and thus the reliability of a stored vehicle was not found in researching for this report. In the conclusions of Chapter VII a recommendation for advanced study in this area is made.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

An astonishing lack of information on the storage of wheeled vehicles was found. This was especially surprising due to the fact that the U.S. Army has millions of dollars of stored inventory in trucks and other wheeled vehicles. However, based on the few studies and reports which were located, the majority of them military reports, some general conclusions about the degradation of vehicles can be made.

Based on the findings of a University of Minnesota report, the element most often responsible for deterioration of stored trucks is corrosion or, in the case of ferrous metals, rust. In a five year study of the four preservation environments used in the Army, rust and corrosion attributed to the environment occured most often in open-air storage, less in the shed, little in the standard warehouse, and none in the controlled-humidity warehouse. Furthermore contact preservation reduced corrosion in all environments an average of 54 percent over domestic preservation. In an economic study of the four environments the standard warehouse with domestic preservation was found to be the most cost effective even though the dehumidified

warehouse stopped corrosion completely. In the light of this data it is concluded that it may be worthwhile to bear the extra expense of maintaining equipment necessary for the security of the United States in a condition that is rust free and ready for operation, but maintaining additional equipment in this condition is unduly costly. For non-emergency items it is recommended that the standard warehouse be used.

In the review of the information found on the economic life of vehicles, it was discovered that the storage of new vehicles will not shorten the economic life length. The storage of an old vehicle with many accumulated miles could, however, shorten the life length of the vehicle depending on the condition of storage. It should be noted that in determining these facts it was assumed that the condition of the vehicle was restored to what it was before storage occurred. Also obsolescence was assumed not a factor in calculating the minimum cost per mile. If these assumptions hold true, care should be exercised whenever storage of old vehicles is considered.

Unfortunately the least information on the most important subjects, reliability and maintainability, was found. Studies found concerning RAM were limited to the parameter, availability. Equations were found for calculating the availability of a stored vehicle, but due to the

lack of knowledge concerning the dormant failure rate, a numerical solution could not be found. Some general trends could be determined, however, that showed a decreasing availability for a constant failure rate and increasing storage period. The same lack of knowledge of the dormant failure rate is responsible for the absence of data concerning reliability of stored vehicles. Intuitively the feeling is that storage degradation lowers the reliability of trucks, but the literature search accompanying this report uncovered no published reports to substantiate that feeling. Therefore it is recommended that an in depth study on reliability of stored trucks be made to determine the actual results of degradation causes by storage.

The reliability of a U.S. Army vehicle is normally established on the basis of mean miles between failure (MMBF). In the examination of reliability, whether or not storage is involved, the MMBF is determined on the basis of the total number of failures recorded relative to some duration of operating time. With this in mind, the recommended in depth study of reliability should take the form of a testing procedure in which trucks are operated and failures recorded.

The testing procedure, mentioned in Chapter VI, developed by TECOM outlines the general steps of reliability testing. Such a test involves placing a test item into

operation to generate the desired parameters (e.g. MMBF, operating time) under specified conditions (e.e. paved highway, cross country, daylight, darkness). Before such a test is initiated decisions must be made as to 1) the number of vehicles on test, 2) the confidence levels that should be kept, 3) the data to be collected during the test, and 4) the conditions of the test. Once these decisions are made preparations for testing can be gotten under way.

The number of vehicles on test and the confidence limits around the results are closely related. In the TECOM test exponential times to failure are assumed and reliability is calculated from recorded data using Equation 2. In Equation 2 an estimate for the MMBF is found by:

$$M = \frac{2T}{X^2_{\alpha,2r+2}} \qquad (12)$$

where,

T = total test time (in miles)
r = number of observed failures
X^2 = α^{th} percentage point of the Chi-Square distribution.

It is known from Roberts (5) that the lower one sided confidence limit of the mean life M is given by:

$$\frac{2r\hat{\theta}_{r,n}}{X^2_{\alpha,2r+2}} \qquad (13)$$

where, $\hat{\theta}_{r,n}$ represents a point estimate of the mean life.

For testing with replacement, as is done in the TECOM test, $\hat{\theta}$ is found, also in Roberts, to be

$$\hat{\theta}_{r,n} = \frac{tn}{r} \qquad (14)$$

where,

t = testing time for 1 vehicle
n = number of items on test
r = total observed failures.

Combining Equations 13 and 14 and realizing that $tn = T$, the total testing time, Equation 12 is obtained. Therefore it is seen that the confidence of the reliability estimate is determined by the confidence of the MMBF estimate, which is related to the number of vehicles on test. From the Aberdeen Proving Ground (APG) (9) study it is found that trucks need only 3750 miles of testing to determine, with a 90 percent confidence level, their MMBF for extended operational periods (over 20,000 miles). With this in mind, at 90 percent confidence ($\alpha = .1$), the number of trucks tested for 3750 miles will determine the accuracy of the reliability estimate. Economics and the availability of stored trucks will determine the number placed on test. Obviously the larger the number, the better the results will be.

The data collected during the test should be sufficient to allow the necessary reliability calculations. Recorded information should include: equipment identification; testing conditions; conditions of the vehicles before testing; identification, result and characteristic of each failure;

the total time (in miles) at each failure; and the total number of failures. Additional information could be kept concerning the test team and their backgrounds but it is not essential.

In determining the conditions for the test, the APG testing procedure recommends a testing course that should be considered. It is one that includes paved road, cross country and belgian block segments sufficient in similarity to actual use conditions to allow only 3750 mile testing times for determining the failure rates. As for the trucks themselves, they should be loaded and serviced to simulate actual gross vehicle weights and maintenance practices.

The trucks for reliability testing can be taken directly from currently stored lots at depots such as Red River Army Depot. Sometimes these types of vehicles are not suitable for formal testing due to the lack of maintenance records that are kept. If this is the case, placing a desired number of trucks in outdoor storage for a maximum of 30 months will simulate most storage degradation that a vehicle will experience. The actual storage time will depend on the length of storage to be simulated. In Appendix A rust count curves are given to illustrate the relative deterioration due to rust. For example, from Figure A-2, if 2 years of standard warehouse storage is to be simulated approximately 8 to 9 months of open air storage would be required,

assuming the same weather conditions prevail. In this manner the outdoor storage will accelerate the testing procedure.

In summary, the results of this research show that standard warehouse storage is the most cost effective method of preventing degradation in vehicles. The reliability and maintainability of vehicles that have experienced long terms of storage are at present unknown, or at best assumed, when a vehicle is reissued. It is recommended that reliability of stored vehicles be determined by testing vehicles that have been subjected to storage.

APPENDIX A

Table A-1

ELECTROCHEMICAL SERIES

Corrosion: In general, when dissimilar metals are exposed in a conducting solution, the more anodic metal will corrode, especially if the anodic area is relatively small. Anode areas nearer the cathode corrode more rapidly.

<u>Anodic or corroded end</u>

Lithium
Rubidium
Potassium
Barium
Strontium
Calcium
Sodium
Magnesium
Beryllium
Aluminum
Manganese
Zinc
Chromium
Iron
Cadmium
Titanium
Cobalt
Nickel
Tin
Lead
Hydrogen
Copper
Silver
Mercury
Palladium
Platinum
Gold

<u>Cathodic or noble-metal end</u>

CLASSIFICATIONS OF RUSTING CONDITIONS

The seriousness of rust is reported as Class I, II, III, or IV. This is the uniform terminology established by the Bureau of Yards and Docks in 1958.

<u>Class I - Stain</u>, discoloration or staining with no evidence of pitting, etching, or other surface damage visible to the naked eye.

<u>Class II - Light Corrosion</u>, surface corrosion, loose rust or corrosion- no tight rust or scale. When removed by wiping, leaves a stain but no evidence of pitting, etching, or other surface damage visible to the naked eye.

<u>Class III - Medium Corrosion</u>, loose or granular rust or corrosion, together with visible evidence of minor pitting or etching.

<u>Class IV - Heavy Corrosion</u>, powdered scale, or tight rust or corrosion together with deep pits, or irregular areas of material removed from the surface.

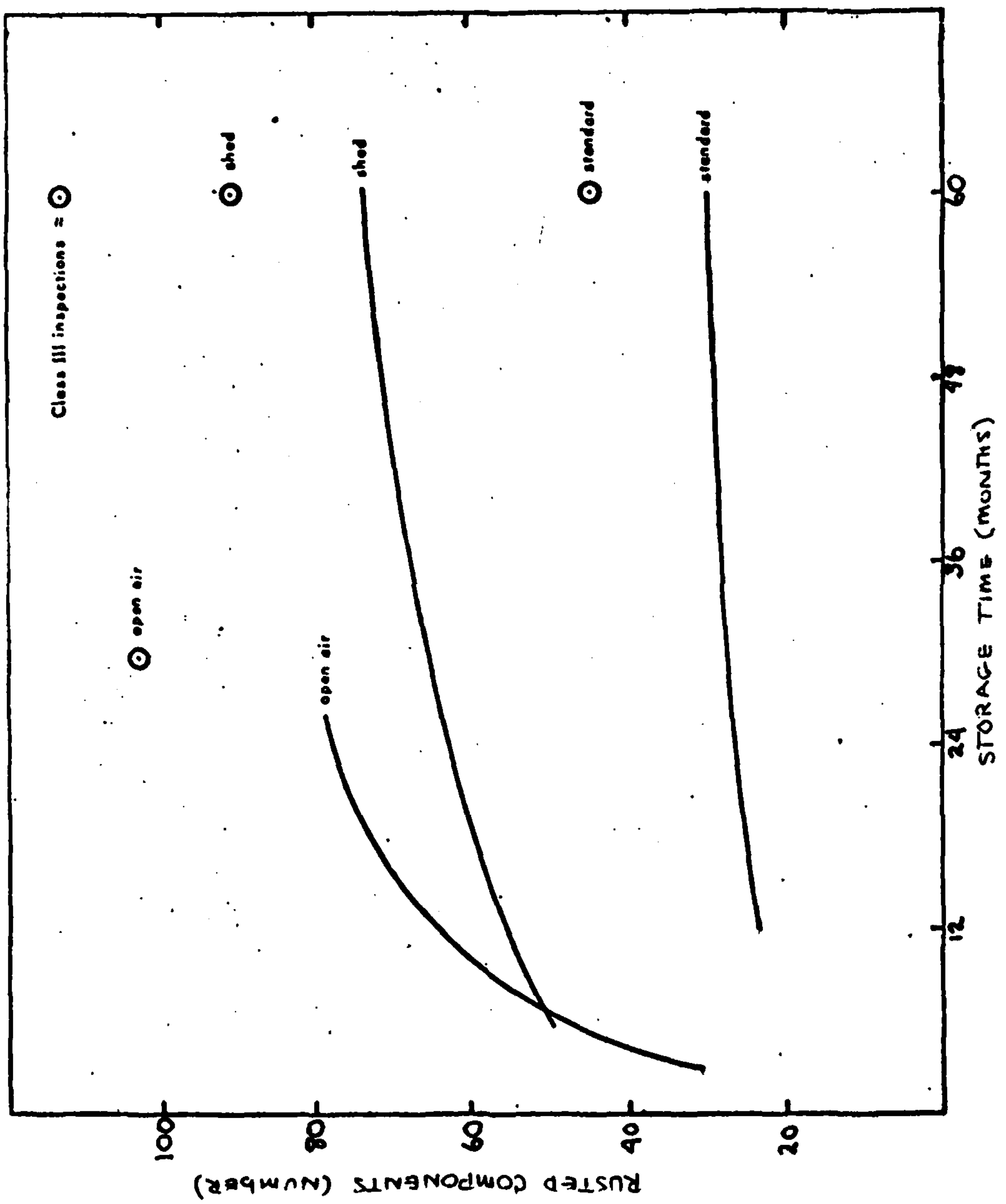

FIGURE A-1. RUST-COUNT CURVES FOR DOMESTIC TREATED ITEMS

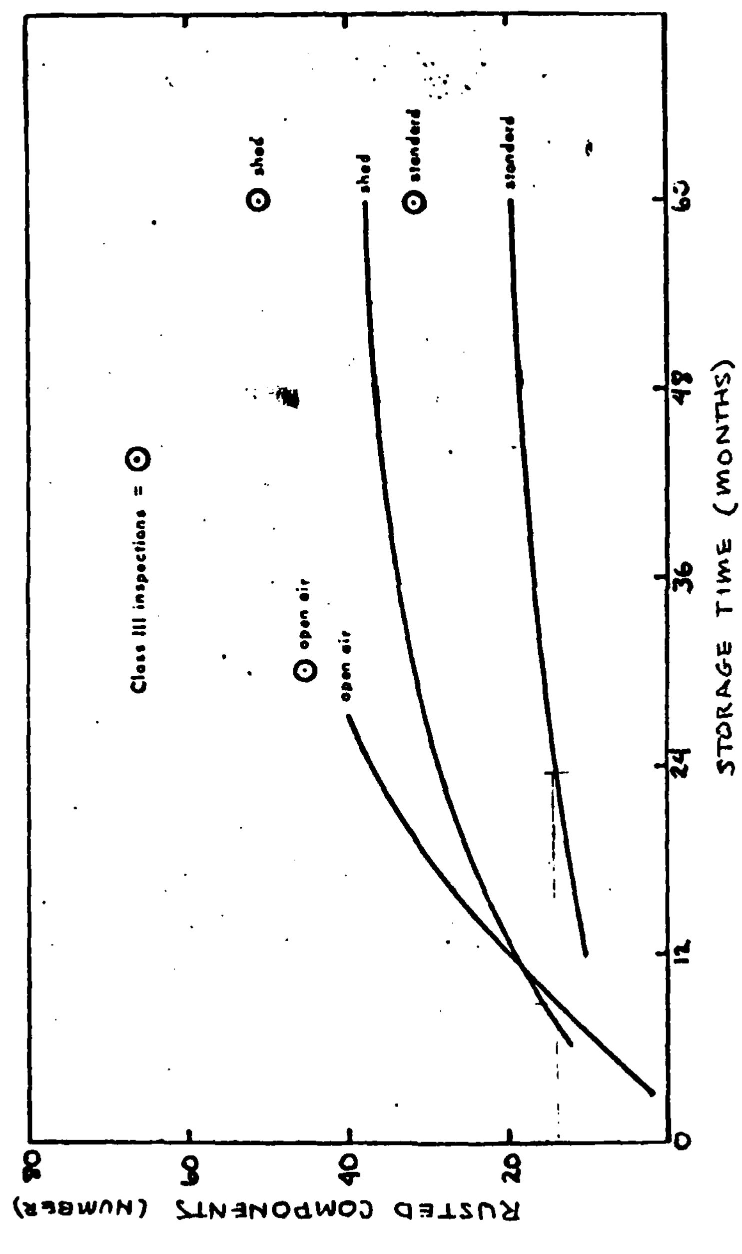

FIGURE A-2. RUST-COUNT CURVES FOR CONTACT PRESERVED ITEMS

APPENDIX B

DESCRIPTION AND EXPLANATION OF COST FACTORS

A - The Labor Hours to Initially Prepare For Storage

Stored equipment was either domestic-treated or contact-preserved. Domestic treatment is furnished by the manufacturer and no additional preservation expense is incurred if the equipment is stored in this condition. But the equipment to be contact-preserved must be partially disassembled, cleaned, preserved, and reassembled; this requires an expenditure of labor.

B - Material Cost to Initially Prepare For Storage

Similar to Factor A, no material costs are incurred if the stored equipment is domestic-treated; they are absorbed by the manufacturer. But contact preservation requires cleaning solvents and preservation materials.

C - Square Footage Required For Storage

The area allotted to each item was based on current warehouse tiering and palleting and service space procedures. Service space, such as aisles, firebreaks, receiving and shipping space, etc., has been set at 40% of the total floor area in a 200-foot by 600-foot warehouse storing equipment similar to that of the NCEL test. A factor of 1.67 was thus used to determine the total space needed for a test item. If an item covered 6 square feet of floor area, it needed 10 square feet (6 x 1.67); however, if a similar item was tiered on top of the first then the space allotment was 5 square feet per item. The same procedure was followed with palleted items.

D - Unit Fixed Cost of Storage Per Square Foot Per Month

Except for the original price of land, this factor took into account all initial costs of the environments amortized over a certain period of time. Included are costs of site

preparation, foundation and slab, building and erection, electrical installation, insulation, exterior painting, and desiccant machinery for the dehumidifying units. Factor D for the test environments giving amortization periods is given in Table B-1.

Table B - 1

	Environment	Cost (ft^2/month)	Amortization Period (yrs)
1.	Open slab	$.0060	10
2.	Shed	.0115	25
3.	Standard warehouse	.0131	25
4.	40% and 50% RH warehouse	.0151	25

E - Storage Maintenance Cost Per Square Foot Per Month

This factor took into account such maintenance and operating expenses as painting (every 3 years), power, and maintenance costs of dehumidifying machinery. Not included were taxes, guard costs, and insurance costs. Factor E for each test environment is given in Table B-2.

Table B - 2

1.	Open Slab	$ 0 /ft^2/month
2.	Shed	.0050
3.	Standard Warehouse	.0063
4.	50% RH Warehouse	.0094
5.	40% RH Warehouse	.0102

F - Labor Hours for Item Inspection

Inspection labor hours upon which this factor is based were determined from the CBS, Port Hueneme time-cost accounting records. These are records of the actual time required to make the equipment inspections at the times specified by the Quality Control Procedures Manual TP-QC-1. These times, when average, become reliable statistical data. The periodic inspections of test items mentioned earlier in the report are the purposes of determining the

state of deterioration only and are not included in Factor F.

G - Labor Hours for Operational Testing Only

There are two parts to the operational tests specified in TP-QC-1. One part tests equipment in dead storage, the other tests new receipts for acceptability. The operational costs are incurred only when the dead storage costs are unsatisfactory.

H - Labor Hours for Depreservation

Before contact-preserved equipment can be placed in service, the preservation material must be removed. If the equipment is to be used stateside, the preservatives are generally removed by the center issuing the equipment. If the equipment is to be shipped overseas, the preservative material is generally left intact for the receiving station to remove. But regardless of who removes the preservative, the removal is a chargeable storage cost. Similar to Factor E, labor hours, H, have been obtained from time-cost accounting records. Depreserving domestic-treated equipment is not necessary since this equipment is stored with service oils and greases and in a ready-to-use condition.

i - Subscript denoting "With respect to type of storage environment."

j - Subscript denoting "With respect to particular item stored."

K - Ratio of Sample Size to Lot Size

Actual periodic field inspections are made on random samples; the number of samples required for inspection is specified by the TP-QC-1 manual. For example, of 25 jeeps, five must be inspected. This gives a sample-to-population ratio of 1:5, which was used in the basic equation. This ratio, however, will vary with different lot sizes, with the percentage of samples decreasing as the lot size increases. In a lot of two to eight items, the sample size would be 4, but for a lot of 66 to 110 items, the sample size would be 7.

L - Hourly Labor Charge

This is the average hourly rate paid to employees associated with the preservation and storage of equipment.

M - Man-Hours for Rehabilitation

N - Material Cost For Crating, Dunnage, Boxing, etc,

All items in storage except automotive equipment are boxed or crated. In general, contact-preserved items are boxed, and domestic-treated items are open-crated. Boxes and crates can be stacked to conserve space, and boxes offer additional protection. Most service items are crated by the vendor and their cost is included in the original price of the items.

P - Original Cost of Item Less Depreciation

To allow for the possibility that an item in storage could deteriorate beyond repair, the expression $S_{ij}P_{jt}$ was included in the formula. If the item cannot be repaired, the remaining value of the item would be added to the storage cost. P should indicate the net value according to accepted accounting procedures of the type of item.

R - Parts Cost For Rehabilitation

This is the cost in dollars of replacement parts for rehabilitation.

S - One (1) if item is found to be unrepairable; zero (0) if otherwise.

t - Subscript denoting "With respect to time."

T - Storage Time in Months

This indicates the total time in months the item has been in any particular storage environment.

U - Number of Inspections

The inspection frequency used for the cost calculation is presented in TP-QC-1. The number of inspections is the whole number obtained from dividing the storage time by the inspection frequency.

V - Number of Operational Tests

The operational testing frequency used in the calculations is presented in TP-QC-1 as every second inspection. No fractional part of the test was considered.

W - Total Storage Cost

This represents the total cost in dollars for the storage of an item within the limits of the Laboratory test.

Y - Ratio of Operationally Tested Items to Lot Size

At every other inspection, an operational test is given to applicable items.

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